Global Eradication of Measles: An Epidemiologic and Economic Evaluation

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Background. Measles remains an important cause of morbidity and mortality in children in developing countries. Due to the success of the measles mortality reduction and elimination efforts thus far, the WHO has raised the question of whether global eradication of measles is economically feasible.

Methods. The cost-effectiveness of various measles mortality reduction and eradication scenarios was evaluated vis-à-vis the current mortality reduction goal in six countries and globally. Data collection on costs of measles vaccination were conducted in six countries in four regions: Bangladesh, Brazil, Colombia, Ethiopia, Tajikistan, and Uganda. The number of measles cases and deaths were projected from 2010 to 2050 using a dynamic, age-structured compartmental model. The incremental cost-effectiveness ratios were then calculated for each scenario vis a vis the baseline.

Results. Measles eradication by 2020 was the found to be the most cost-effective scenario, both in the six countries and globally. Eradicating measles by 2020 is projected to cost an additional discounted $7.8 billion and avert a discounted 346 million DALYs between 2010 and 2050.

Conclusions. In conclusion, the study found that, compared to the baseline, reaching measles eradication by 2020 would be the most cost-effective measles mortality reduction scenario, both for the six countries and on a global basis.

Measles is one of the most infectious and severe diseases of childhood and remains an important cause of morbidity and mortality in developing countries. During 2005, a global goal of 90% reduction in measles-related mortality by 2010 (compared with 2000) was adopted [1]. In recent years, with the support of the World Health Organization (WHO), United Nations Children's Fund (UNICEF), and the Measles Initiative (Launched in 2001, the Measles Initiative is an international partnership committed to reducing measles-related deaths worldwide, and is led by the American Red Cross, the Centers for Disease Control and Prevention, UNICEF, United Nations Foundation, and the WHO. Additional information available at http://www.measlesinitiative.org.), countries have accelerated their efforts to reduce measles-related morbidity and mortality both through increasing routine measles immunization coverage (RI) and conducting periodic campaigns known as supplementary immunization activities (SIAs). During 2000–2008, these activities reduced global measles-associated mortality by an estimated 78% (achieving an estimated >90% mortality reduction in the Eastern Mediterranean, the African regions, and the Western Pacific WHO Regions) [2]. In addition, high coverage of 2 doses of measles vaccine (delivered through routine programs with or without campaigns) eliminated measles from the American WHO Region by November 2002.

Because of the success of the measles-associated mortality reduction and elimination efforts thus far, WHO member states requested an assessment of whether global eradication of measles is programmatically, biologically, and economically feasible. Five of the 6 WHO Regions have already adopted regional measles elimination targets [3], with the remaining region, SouthEast Asia, pursuing a mortality reduction goal in

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Potential conflicts of interest: none reported.

Supplement sponsorship: This article is part of a supplement entitled "Global Progress Toward Measles Eradication and Prevention of Rubella and Congenital Rubella Syndrome," which was sponsored by the Centers for Disease Control and Prevention.

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The Journal of Infectious Diseases 2011;204:S98–S106

0022-1899 (print)/1537-6613 (online)/2011/204S1-0015$14.00
DOI: 10.1093/infdis/jir096

line with the planned global measles control targets [1]. Although this assessment of the feasibility of measles eradication was undertaken, a 95% global mortality reduction goal by 2015 (compared with 2000) was adopted by the WHO World Health Assembly in May 2010 [3].

Several factors work in favor of measles eradication: humans are the only hosts, measles vaccine is highly efficacious, and immunity resulting from infection and/or vaccination is very durable [4]. In this analysis, we use the definition of eradication used in the WHO-UNICEF 2001–2005 Measles Strategic Plan: "the interruption of measles transmission worldwide as a result of deliberate efforts; intervention methods may no longer be needed. Eradication represents the sum of successful elimination efforts in all countries" [5]. By comparison, mortality reduction means that incidence may be low in most countries, but unbroken chains of transmission remain.

The objectives of this study were to (1) estimate the cost and cost-effectiveness of measles eradication and intermediate goals of 95% and 98% mortality reduction, compared with the baseline scenario (the 90% measles-associated mortality reduction global goal) in 6 countries, and (2) extrapolate this analysis to the global level to determine cost and cost-effectiveness of global measles eradication.

METHODS

Countries and Scenarios

Data collection and analyses of measles-associated mortality reduction were conducted in 6 countries, because it was not feasible to do so in all countries. The countries were chosen to ensure diversity of costs with use of the following criteria: (1) measles first dose coverage and (2) gross national income per capita levels. Costs and health outcomes were evaluated using the following 4 scenarios in Bangladesh, Brazil, Colombia, Ethiopia, Tajikistan, and Uganda: (1) 90% mortality reduction by 2013 (baseline), (2) 95% mortality reduction by 2015 (95% RM), (3) 98% mortality reduction by 2020 (98% RM), and (4) eradication of measles by 2020 (E2020).

Eradication of measles by 2025 was also evaluated under varying posteradication vaccination strategies (results not shown). The baseline scenario assumes 2013 as the target date for 90% mortality reduction, because at the time of publication, those countries that did not meet the original target date of 2010 were expected to do so by 2013.

Transmission Model

To capture the herd immunity effects that ultimately make eradication possible, a dynamic (transmission) model was performed for the period 1950–2050 and projected the number of measles cases and associated deaths with use of the aforementioned scenarios for each country beginning in 2010 (Appendix S1). The model stratifies the population by age (<1 year, 1–2 years, 3–5 years, 6–15 years, or ≥16 years) and infection status (susceptible, exposed, infectious, or recovered). Individuals move between these compartments (for instance, because of aging or infection) at specified rates. Births and deaths were modeled stochastically to capture the impact of demographic stochasticity on disease dynamics [6]. Transmission rates were based on a matrix of age-specific contact rates related to household size and varied according to seasonal patterns. Administration of vaccine removed individuals directly to the recovered compartment from the susceptible compartment, in proportion to vaccination coverage and effectiveness. Each of the 6 countries was divided into a number of districts, and the aforementioned compartmental model was performed in each district. Stochastic case imports could come from other districts or from sources outside the country. The model results reported are mean outputs produced from 10 stochastic realizations of the model for each scenario.

Parameter values were country specific and obtained from primary data collection in each of the 6 countries and from published literature (see Table 1). The resulting transmission model was validated for the 6 case-study countries against annual district- or country-level incidence calculated from historical case notifications, based on data availability. The model captured realistic biennial and longer-term outbreak frequency and size (Figure 1) and reductions in transmission after the introduction of vaccination that corresponded to historical observed reductions in incidence.

Immunization Program Assumptions

Vaccine efficacy of a single dose was 85% among children 9–11 months of age and 95% among children ≥12 months of age [13], and protection was assumed to be life-long. Vaccine could be administered through (1) routine first-dose (MCV1) vaccination at 9 or 12 months of age, (2) routine second-dose (MCV2) vaccination during the second year of life or at school entry (for countries already using this vaccination schedule), (3) SIAs, or (4) outbreak-response campaigns. In accordance with the WHO guidelines, MCV2 was introduced during the second year of life after the national mean MCV1 coverage remained at least 80% for 3 consecutive years [14]. Follow-up SIAs were assumed to cover 90% of children aged 9 months to 4 years over a 6-week period. SIA frequency was assumed to remain stable on the basis of current levels of funding and varied on the basis of country-specific MCV1 coverage and the time required to achieve the mortality reduction or eradication goal. Outbreak response vaccination was introduced in 2010 and was triggered when weekly measles incidence in a given district exceeded 20 cases per 1,000,000 population, beginning 4 weeks after outbreak detection, and covering 90% of individuals in the age groups that account for 90% of cases.

The probability that an individual receives MCV2 depended on whether MCV1 had been received. For MCV2 administered during the second year of life, 25% of previously unvaccinated

Table 1. Transmission Model Parameter Values

Model Parameter	Description	Baseline value	Lower, Upper Range	Reference
b_t	Birth rate, year *t*	Varies according to district	–	Primary data collection, UN Population Division
μ_t	Background death rate, year *t*	Varies according to district	–	Primary data collection, UN Population Division
β_{ij}	Rate of transmission from an infectious person of age class *j* to a susceptible person of age class *i*	See Section on transmission rate	–	Calibrated, [7]
α	Seasonal forcing amplitude	See Section on transmission rate	+/− 50%	[6]
$1/\sigma$	Mean incubation period	9 days	–	[8], [9]
$1/\gamma$	Mean effective infectious period*	7 days	–	[8], [9]
$\mu_{M,k}$	Case fatality rate in age class *k*	Varies according to country	+/− 50%	Primary data collection, WHO guidance
$e_{<1}$	% immune after 1 dose, <1 year	85%	–	[10], [11], [12]
$e_{>1}$	% immune after 1 dose, > 1 year	95%	–	[10], [11], [12]
	Vaccine coverage, MCV1, in age class *k* at year t	Varies according to district	–	Calibrated
	Vaccine coverage, MCV2, in age class *k* at year *t*	Varies according to district	–	Calibrated
	Vaccine coverage, SIA, in age class *k* at year *t*	Varies according to district	–	Calibrated
	Vaccine coverage, outbreak response, in age class *k* at year *t*	Varies according to district	–	Calibrated
D(s)	Degree of dependence between MCV1 and MCV2	75% for MCV2 at 15-18mo, 25% for MCV2 at school entry	+/− 15%	WHO expert consensus
T_{mn}	Proportionality constant governing importation of cases from district *m* to district *n*	Varies according to country	–	Calibrated
ω	Gaussian noise term for demographic stochasticity		–	Calibrated
M	Parameter governing how quickly case imports decline as global eradication is approach	Varies according to scenario		Calibrated

children received MCV2, whereas 75% of previously vaccinated children received the vaccine; for MCV2 given at school entry, this figure was 75% (25% for previously vaccinated children).

The vaccine coverage was tuned or calibrated so that goals could be reached by the scenario target dates. To achieve this, the level and types of vaccine coverage were adjusted in the following order: (1) increase MCV1 coverage, and if appropriate, increase age of MCV1 from 9 to 12 months after 95% reduction in mortality is achieved; (2) introduce and/or increase MCV2 coverage; (3) increase coverage and/or frequency of SIAs; and (4) implement outbreak-response vaccination. Reduction in mortality goals is considered to be attained if the mean percentage reduction in mortality, compared with 2000 levels, for postgoal years is within 1% of the target. After eradication was achieved, it was assumed that only first and second routine doses of measles vaccination would be continued, whereas SIAs would be discontinued. In the eradication scenarios, a 3-year certification period was allowed before SIAs were discontinued; thus, for the E2020 scenario, SIAs were discontinued in 2023.

Cost Estimation

The cost of measles eradication in a given country was defined as the aggregate incremental cost that would be needed to achieve eradication (ie, above the costs that would be incurred to achieve a lower level target; eg, a 90% reduction in mortality by 2013, compared with the 2000 baseline).

To estimate the costs of each specific strategy, the projected annual program costs were summed for the measles immunization activities for each scenario, country, and year until measles eradication was achieved. After eradication was achieved, the costs of maintaining it were estimated for each country until 2030 (results not shown) and 2050. The mean cost per dose was estimated by dividing total annual costs by the number of doses administered.

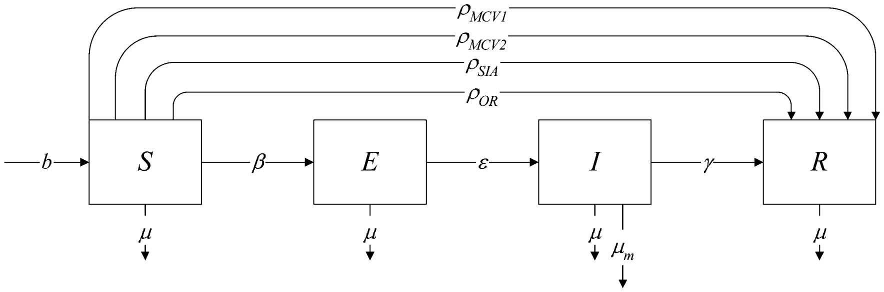

Figure 1. Transmission model diagram.

The costs of routine immunization and SIAs were estimated using an ingredients approach [15], to include the following:

$$\begin{aligned} \mathrm{TC} = {} & \mathrm{cost_{pers}} + \mathrm{cost_{vacc}} + \mathrm{cost_{is}} + \mathrm{cost_{t}} \\ & + \mathrm{cost_{main}} + \mathrm{cost_{sm}} + \mathrm{cost_{ms}} + \mathrm{cost_{cc}} \end{aligned}$$

where "pers" is personnel, "vacc" is vaccines, "is" is injection supplies, "t" is transportation, "sm" is social mobilization, "ms" is monitoring and surveillance, and "cc" is capital costs. When applicable, the cost of measles-rubella or measles-mumps-rubella vaccine were substituted for measles vaccines. The direct costs and/or savings from not treating averted measles cases was also estimated using available data on the costs of treatment (see online appendices for sources of data).

The indirect or societal costs of obtaining measles vaccinations (transportation, travel, and waiting time), both at routine immunization and SIAs, were estimated on the basis of interviews with clients bringing children for vaccination and/or of published data.

The cost per dose of reaching measles-associated mortality or global eradication goals was assumed to increase with higher RI and SIA coverage levels. These additional and increasing costs were estimated by determining the cost of the inputs that are

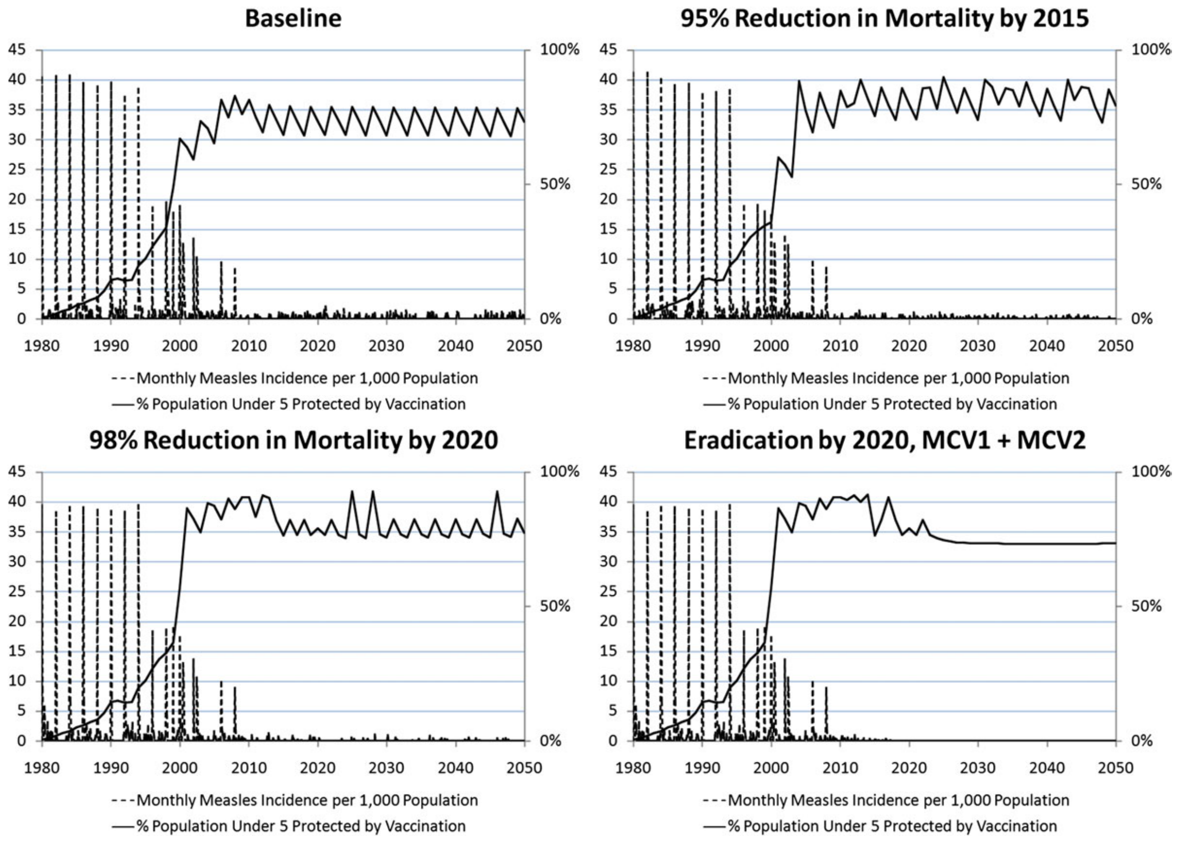

Figure 2. Time series of monthly measles incidence and percentage of population under 5 protected by vaccination in Ethiopia under baseline, 95% RM by 2015, 98% RM by 2020, and E2020.

needed to enhance measles vaccination (ie, increase routine coverage [MCV1 and MCV2], including outreach activities, by reaching hard-to-reach populations, improving surveillance in the country, and conducting more frequent SIAs). For routine immunizations and SIAs, the cost of reaching hard-to-reach populations would increase because of lower productivity rates (ie, fewer children seen per provider per day at fixed sites and outreach sessions), higher wastage rates, higher transportation costs, and improved measles surveillance).

The prices of vaccines and injection supplies were based on current UNICEF prices and wastage rates in country-comprehensive multiyear plans. Shared costs for routine vaccination were allocated by assuming the percentage of doses of measles vaccine to total number of doses of vaccines. Capital costs were only included if additional cold chain equipment, vehicles, and laboratory equipment would be purchased for measles eradication activities.

In these scenarios, all prices and improved efficiencies are assumed to increase at the same rate (ignoring potential lower costs because of the introduction of new vaccine formulations [eg, an aerosol vaccine]). Discounting of both costs and benefits used a rate of 3% [16].

The study team collected cost data from various sources: WHO headquarters and regional offices and visits to 6 countries. During the country visits, the study team (1) collected data on costs of conducting routine vaccination, SIAs, and surveillance from country immunization program offices and WHO offices; (2) conducted interviews with key stakeholders regarding the resources required to increase coverage of routine vaccination, SIAs, and surveillance to achieve measles eradication; and (3) traveled to a sample of districts and/or regions to collect information on local resources used for measles vaccination activities.

Economic Evaluation: Cost-Effectiveness Analysis

The costs estimated for each scenario were combined with outcome measures obtained from the dynamic transmission modeling. These measures include measles cases and/or deaths averted and disability-adjusted life-years (DALYs) averted for each strategy. Estimates of incremental costs and DALYs averted over the baseline for each of the scenarios were used to calculate incremental cost-effective ratios (ICERs) for the period 2010–2050.

Sensitivity analysis was conducted on key epidemiological and cost parameters (eg, discount rate, case-fatality rates, vaccine wastage rates, and vaccine prices) that have uncertainty. Intervals were defined around each baseline parameter value, from which samples were taken for probabilistic uncertainty analysis.

The cost-effectiveness of the 4 scenario strategies was judged against the Commission on Macroeconomics and Health threshold that the cost per DALY be <3 times the per capita national gross domestic product for each country.

Global Extrapolation

For the global analysis, the existing transmission model was used, but the districts in the model represented 180 countries (rather than districts in a country), and between-district transmission represented case imports between countries. The following parameters were defined with country-level values: (1) annual demographic data (age-specific population, birth and death rates, and age-specific life expectancy), (2) case-fatality ratios, (3) historical routine vaccination coverage levels and timing and coverage of SIAs, and (4) target coverage levels for projected vaccination activities.

A single global contact matrix was derived from the mean global household size, as described above.

The mean outputs of at least 3 iterations of the model for cases, deaths, and vaccinations were then distributed among all countries grouped in 8 subgroups in 2 dimensions: income (low, lower-middle, upper-middle, or high-income subgroups) and elimination status (whether the country has or has not eliminated measles transmission on a national scale). Elimination status was determined from the historical percentage of global cases and vaccinations for each country.

For each of these country subgroups, total and incremental costs and ICERs were derived on the basis of income group–specific estimates for (1) cost per dose for routine and SIA vaccination, (2) cost to household, and (3) cost of case treatment. The increasing cost curve estimated from the 6 countries was applied to the other countries to make the global extrapolation. In countries that have already eliminated measles except for occasional outbreaks caused by importations, the cost of measles outbreaks was estimated.

RESULTS

Transmission Model

The predicted number of cases over time and the percentage of children protected through vaccination for Ethiopia are shown in Figure 2. The biennial character of measles epidemiology is apparent, as is the gradual extinction of measles, because vaccine coverage is ramped up through improvements in routine vaccination and SIAs. Of note, a significant ramp-up of routine vaccination and outbreak response is required to move from 95% reduction in mortality to 98% and eradication.

The scenarios of 95% and 98% mortality reduction and eradication by 2020 (with discontinued SIAs after eradication) have a considerable impact on total cases and deaths relative to the baseline strategy (Table 2). In countries that have not yet eliminated measles (Bangladesh, Ethiopia, Tajikistan, and Uganda), this is attributable largely to their progress towards scenario goals. However, in countries that have already eliminated measles (Brazil and Colombia), fewer cases and deaths occur because of lower case importation as remaining countries where measles is endemic eliminate measles.

Table 2. Total Cases and Deaths for Individual Countries and Global Analysis, 2010–2050, With a Baseline of 90% Mortality Reduction

	CASES (000s)				DEATHS			
	Baseline	95% RM	98% RM	E2020	Baseline	95% RM	98% RM	E2020
Individual Country Results								
Bangladesh	30,747	16,682 (54%)	16,293 (53%)	2,632 (9%)	200,000	134,000 (67%)	129,000 (65%)	20,000 (10%)
Brazil	3	2 (67%)	2 (67%)	1 (17%)	2	2 (100%)	2 (100%)	(0%)
Colombia	8	6 (75%)	6 (75%)	1 (13%)	2	1 (50%)	1 (50%)	(0%)
Ethiopia	12,071	5,990 (50%)	3,162 (26%)	832 (7%)	147,000	88,000 (60%)	46,000 (31%)	12,000 (8%)
Tajikistan	122	43 (35%)	41 (34%)	9 (7%)	500	200 (40%)	200 (40%)	40 (8%)
Uganda	795	436 (55%)	219 (28%)	30 (4%)	20,000	12,000 (60%)	7,000 (35%)	900 (5%)
Global Results: Countries which have not eliminated measles by 2010								
Low Income (42)	390,483	193,573 (50%)	73,393 (19%)	25,123 (6%)	2,297,000	1,106,000 (48%)	459,000 (20%)	161,000 (7%)
Low-mid Income (41)	3,516,035	194,473 (6%)	660,856 (19%)	226,217 (6%)	20,682,000	1,110,000 (5%)	4,129,000 (20%)	1,447,000 (7%)
Upper-mid Income (24)	188,183	93,287 (50%)	35,370 (19%)	12,107 (6%)	1,107,000	533,000 (48%)	221,000 (20%)	77,000 (7%)
Upper Income (39)	18,778	1,039 (6%)	3,529 (19%)	1,208 (6%)	110,000	6,000 (5%)	22,000 (20%)	8,000 (7%)
Global Results: Countries which have eliminated measles by 2010								
Low-mid Income (16)	24,554	12,172 (50%)	4,615 (19%)	1,580 (6%)	144,000	69,000 (48%)	29,000 (20%)	10,000 (7%)
Upper-mid income (19)	30,448	15,094 (50%)	5,723 (19%)	1,959 (6%)	179,000	86,000 (48%)	36,000 (20%)	13,000 (7%)
Upper income (12)	631	35 (6%)	16 (3%)	9 (1%)	4000	200 (5%)	100 (3%)	60 (2%)

NOTE. Percentage between brackets refers to the percentage of cases or deaths of the baseline.

For the global analysis, in countries with low current mean routine vaccination coverage levels (<70%), vaccinations were assumed to ramp up under mortality reduction and eradication scenarios to achieve the goal by the target date.

On the basis of the sensitivity analysis performed on the transmission model, the key drivers of cases and deaths include (1) measles case-fatality ratio and (2) probability of case importation from outside the country. However, qualitative results with respect to the cost-effectiveness of eradication remain the same under the range of parameter values explored.

Cost Estimation

Table 3 presents the cost estimates for measles vaccination for each country. The cost of a dose of measles vaccine is shown for routine vaccination and for SIAs. The estimated mean cost per dose of routine vaccination is smaller in low-income countries, ranging from $1.35 in Ethiopia to $7.77 in Colombia. The cost of delivering a dose through SIAs was less expensive than through routine vaccination, ranging from $0.52 in Bangladesh to $2.87 in Colombia. The estimates of additional costs of increasing routine vaccination coverage range from an additional $0.04 per percentage point increase in coverage level per dose in Uganda to $0.075 in Tajikistan.

Cost-Effectiveness

Table 4 shows the total costs, incremental costs, and ICERs of reaching the 95% mortality reduction, 98% mortality reduction,

Table 3. Estimated Cost Per Dose of Measles Immunization by Country

	Uganda	Ethiopia	Bangladesh	Tajikistan	Colombia	Brazil
Current routine measles coverage	68%	63%	85%	86%	95%	94%
Average cost per dose of routine immunization	$2.35	$1.35	$1.46	$1.68	$7.77	$3.91
Cost per dose of SIA	$1.24	$0.64	$0.52	$0.62	$2.87	$1.27
Added cost per additional percent of coverage for routine immunization	+$0.04 until 80%; $0.08 for 80%+	$0.055 until 80%; $0.118 for 80%+	0.07 until 90%; .15 for 90%+	$0.075 until 90%; $0.15 for 90%+	N/A	N/A
Household cost of obtaining measles immunization	$0.58	$0.25*	$0.50	$0.72	$3.80	$1.43
Cost of treating a case of measles	$6.00	$12.34	$12.40	$12.95	$85.00	$198.50

NOTE. *Household cost of measles immunization is low in Ethiopia since services are provided by community workers.

Table 4. Country ICERS for 95% and 98% Reduction in Mortality and E2020 Global Goals Relative to Baseline of 90% Reduction in Mortality

	Strategy	Total cost (Millions, 2010 USD)	Incr. cost (Millions, 2010 USD)	Total DALYs	Incr. DALYS Averted	ICER,$ per DALY Averted (2010 USD)	GDP per Capita (2009)
Bangladesh	Baseline	$340	–	3,684,549	–	–	$551
	95%RM	$655	$315	2,466,202	1,218,000	$259	
	98%RM	$645	$305	2,394,268	1,290,281	$236	
	E2020	$388	$49	513,412	3,126,000	$16	
Ethiopia	Baseline	$254	–	2,396,529	–	–	$345
	95%RM	$405	$151	1,602,620	794,000	$190	
	98%RM	$645	$391	829,133	1,567,396	$250	
	E2020	$533	$280	312,528	2,084,000	$134	
Tajikistan	Baseline	$30	–	8,843	–	–	$716
	95%RM	$61	$31	4,662	4,181	$7,319	
	98%RM	$60	$30	4,276	4,567	$6,639	
	E2020	$41	$10	1,174	7,669	$1,355	
Uganda	Baseline	$229	–	523,235	–	–	$481
	95%RM	$578	$349	206,416	316,819	$1,102	
	98%RM	$774	$545	124,776	398,459	$1,369	
	E2020	$630	$401	24,619	498,616	$804	
Brazil	Baseline	$1,527	–	52	–	–	$8,070
	95%RM	$1,492	($35)	44	8	Cost/life saving	
	98%RM	$1,400	($127)	40	13	Cost/life saving	
	E2020	$1,107	($419)	15	37	Cost/life saving	
Colombia	Baseline	$925	–	49	–	–	$4,950
	95%RM	$918	($7)	36	13	Cost/life saving	
	98%RM	$920	($5)	38	10	Cost/life saving	
	E2020	$833	($92)	10	39	Cost/life saving	

and eradication goals. Among countries that have not eliminated measles, the costs of measles vaccination during 2010–2050 are projected to increase as the program ramps up its activities to reach these goals. In comparison with 95% reduction in mortality, eradication would require additional resources in Ethiopia and Uganda to achieve a coverage level sufficient to stop transmission, whereas eradication would require fewer resources in Bangladesh and Tajikistan because of cost savings from reductions in outbreak response and SIAs, because these countries already have high coverage.

In Ethiopia and Uganda, it would be more costly to achieve the 98% reduction in mortality goal in comparison with 95% reduction in mortality. On the other hand, the other countries would experience cost savings from fewer outbreak response activities as case importation decreases. For all 6 countries, eradication is a less costly option than 98% reduction in mortality because of cost savings from discontinuing SIAs after 2023.

On the basis of the sensitivity analysis performed on the model, the key drivers of costs of reaching measles mortality reduction or eradication goals are the following: (1) initial cost per dose for routine vaccination, (2) cost per percentage point increase in routine and campaign coverage, and (3) cost of treating a measles case. As with sensitivity analysis on the transmission parameters, cost-effectiveness qualitative results are maintained under the range of parameters explored.

For the 2 countries that have eliminated measles (Brazil and Colombia), it is assumed that they would benefit from reduced case importation from other countries working toward measles elimination. Because less outbreak response would be required, vaccination costs in these countries would decrease to reach any of the 3 vaccination goals.

All ICERs for 95% mortality reduction relative to baseline are cost-effective, being lower than the commonly cited threshold of 3 times the gross domestic product per capita, except for Tajikistan. (Of note, there were some data quality issues in Tajikistan, such as possible under-reporting of cases that may account for the high cost per DALY averted in the country.) (Table 4). For the 2 countries that have already eliminated measles, both costs and lives are saved and the ICERs are considered to be cost and life-saving.

ICERs for the 2020 eradication scenario in the 4 countries that have not eliminated measles meet the criteria of being cost-effective; 2 are considered to be very cost-effective because the ICERs are less than the gross domestic product per capita. The ICERs are more cost-effective for this scenario than for reaching the 95% mortality reduction scenario because of cost savings

Table 5. Global ICERs for 95% and 98% Reduction in Mortality and E2020 Goals Relative to Baseline

	Strategy	Total cost (Millions, 2010 USD)	Incr. cost (Millions, 2010 USD)	Total DALYs (000s)	Incr. DALYS Averted (000s)	ICER,$ per DALY Averted (2010 USD)	GDP per Capita (2009)
Countries which have not eliminated measles by 2010							
Low (42)	Baseline	$903	–	37	–	–	$480
	95%RM	$1,088	$185	16	21	$9	
	98%RM	$1,213	$310	8	42	$11	
	E2020	$1,040	$137	137	32	$4	
Low-mid (41)	Baseline	$10,825	–	333	–	–	$2,078
	95%RM	$10,617	($208)	18	316	Cost/life saving	
	98%RM	$11,953	$1,128	75	258	$4	
	E2020	$10,529	($296)	41	292	Cost/life saving	
Upper-mid (24)	Baseline	$1,692	–	18	–	–	$7,604
	95%RM	$1,786	$94	8	10	$9	
	98%RM	$1,947	$255	4	14	$18	
	E2020	$1,759	$67	2,207	16	$4	
Upper (39)	Baseline	$45,607	–	1,778	–	–	$38,551
	95%RM	$56,635	$11,029	94	1,684	$6,548	
	98%RM	$63,156	$17,549	400	1,378	$12,737	
	E2020	$53,823	$8,216	229	1,558	$5,274	
Countries which have eliminated measles by 2010							
Low-mid (16)	Baseline	$1,091	–	2,325	–	–	$2,442
	95%RM	$1,082	($12)	996	1,329	Cost/life saving	
	98%RM	$1,530	($14)	524	1,802	Cost/life saving	
	E2020	$1,069	($140)	288	2,037	Cost/life saving	
Upper-mid (19)	Baseline	$2,172	–	2,888	–	–	$8,302
	95%RM	$2,148	($25)	1,235	1,648	Cost/life saving	
	98%RM	$2,146	($27)	649	2,234	Cost/life saving	
	E2020	$2,068	($104)	357	2,526	Cost/life saving	
Upper (12)	Baseline	$4,053	–	60	–	–	$43,659
	95%RM	$4,052	($1)	3	57	Cost/life saving	
	98%RM	$4,052	($1)	2	58	Cost/life saving	
	E2020	$4,006	($47)	2	58	Cost/life saving	

from stopping outbreak response and SIAs. In the 2 countries that have eliminated measles, eradication by 2020 would be both cost and life-saving (thus, an ICER cannot be computed).

Table 5 shows the global ICERs by income group and elimination status. For countries that have not eliminated measles, ICERs in 3 of 4 of the income groups are projected to be very cost-effective for both of the global goals of 95% mortality reduction by 2015 and eradication by 2020. In the fourth income group (lower middle income), both goals were projected to be cost and life-saving. For the countries that have eliminated measles, the incremental impact is projected to be both cost and life-saving for the 3 income groups.

DISCUSSION

The most cost-effective scenario is global eradication by 2020, both for the 6-case study countries and for the global income and elimination status groups. Eradication would be particularly beneficial for countries that have already eliminated measles, because costs and lives would be saved with fewer case importations and reduced need for outbreak responses. These findings are an incentive for elimination countries to invest in an eradication initiative.

The 95% reduction scenario is also cost-effective for 5 of the 6 countries, but averting a DALY loss through this strategy is more costly than with eradication by 2020 because of the greater costs of maintaining reduced mortality levels through continued SIAs and outbreak response. Eradication by 2025 was also cost-effective but less than by 2020 (results not shown).

In terms of estimated program costs, the incremental aggregate discounted costs for eradication by 2020 during 2010–2050 were estimated to be $7.8 billion (see Table 5), comprised largely of vaccination services in nonelimination high-income countries where the delivery costs are greater, followed by costs in low-income countries (see supplemental Appendices).

As in any model, our analysis required making ce brtain assumptions. Achieving measles elimination requires high-quality SIAs, improvements in routine vaccination, and good surveillance. We also did not take into account the possibility of reintroduction of the measles virus through terrorism or accident. Some of the costs of improving routine vaccination could be underestimated; because no data on the costs of improving routine vaccination were available, it was necessary to estimate the additional resources required on the basis of a planning model, which may leave out unforeseen costs. In addition, no data were collected in countries that could have the largest incremental costs of reaching the level required for eradication (eg, conflict countries and countries where polio elimination has been challenging). We assumed that all countries would be pursuing reduction in mortality and eradication goals simultaneously. However, countries that lag behind in achieving goals could continue to spark outbreaks globally, which would cause these results to underestimate total cases and costs.

Although some of these assumptions will almost certainly not hold true in future years, our sensitivity analysis indicates that eradicating measles by 2020 remains cost-effective under many conditions, such as a 5-year delay in achieving eradication, various increased costs, or increased case importation. Moreover, the estimated cost per DALY averted under E2020 is lower than that for many other low-cost public health interventions (such as HIV counseling and testing, management of acute respiratory illness, or prevention of road accidents [16]). Therefore, eradicating measles appears to be an attractive approach on economic grounds.

Supplementary Data

Supplementary data are available at *The Journal of Infectious Diseases* online.

Funding

This work was funded by the World Health Organization.

Acknowledgments

The authors alone are responsible for the views expressed in this publication, and they do not necessarily represent the decisions, policy, or views of the World Health Organization.

References

1. World Health Organization. GIVS: global immunization vision and strategy 2006–2015. Geneva: World Health Organization and UNICEF, 2005. http://www.who.int/vaccines-documents/docspdf05/givs_final_en.pdf. Accessed 24 August 2010.
2. Centers for Disease Control and Prevention. Global measles mortality, 2000—2008. MMWR Morb Mortal Wkly Rep **2009**; 58:1321–6.
3. SIXTY-THIRD World Health Assembly May 2010, A63/18, Geneva, Switzerland: World Health Organization.
4. Dabbagh, Alya. Presentation on "Assessing the feasibility of global measles elimination" at Meeting of the Sage Working Group on Measles, January 29-30, Geneva, Switzerland: World Health Organization.
5. Griffin DE, Moss WJ. Can we eradicate measles? Microbe **2006**; 1:409–13.
6. Cutts FT. The immunological basis for immunization: Measles. WHO/EPI/GEN/93.17, 1993. Unpublished document.
7. Weekly epidemiological record. Measles Vaccine. WHO position paper. Wkly Epidemiol Rec **2009**; 35:349–60.
8. World Health Organization. WHO Guide for standardization of economic evaluations of immunization programmes. http://www.who.int/werWHO. Accessed 24 August 2010.
9. Gold M, Siegel J, Russell L, Weinstein M. Cost-effectiveness in Health and Medicine. New York: Oxford University Press, 1996.
10. Bauch CT, Earn DJD. Transients and Attractors in Epidemics. Proc Biol Sci **2003**; 270:1573–8.
11. Mossong J, Hens N, Jit M, et al. Social contacts and mixing patterns relevant to the spread of infectious diseases. PLoS Med **2008**; 5:0381–91.
12. AAP. Measles. Pickering L ed: Red Book: 2006 Report of the Committee on Infectious Diseases, 27th ed. Elk Grove Village, IL: American Academy of Pediatrics, **2006**; 441–52.
13. Collier L, Oxford J. Human Virology, 3rd ed. New York: Oxford University Press, **2006**.
14. Otten M, Okwo-Bele J, Kezaala R, Biellik R, Eggers R, Nshimirimana D. Impact of alternative approaches to accelerated measles control: experience in the African region, 1996–2002. J Infect Dis **2003**; 187(Suppl. 1);S36–43.
15. Hull H, Williams P, Oldfield F. Measles mortality and vaccine efficacy in rural West Africa. Lancet **1983**; 1:972–5.
16. Samb B, Aaby P, Whittle H, Seck A, Simondon F. Protective efficacy of hightitremeasles vaccines administered fromthe age of five months: a community study in rural Senegal. Trans R Soc Trop Med Hyg **1993**; 87:697–701.